

Electrochemical Power Sources for Venus Exploration

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KISS Workshop at Caltech

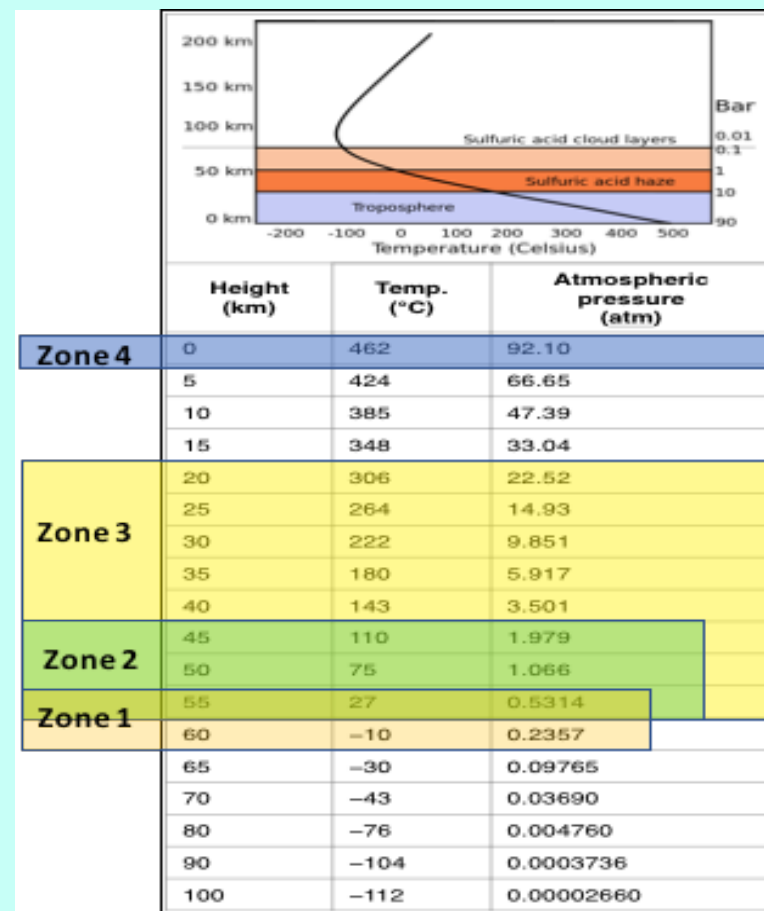
December, 7, 2017

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Venus Atmospheric Missions Limited by Its Environmental Severity

- Venus has a hostile environment with high temperatures and high CO₂ pressure, both increasing with a decrease in altitude.
 - 465°C and 92 atm at the surface
 - 27°C and 0.5 atm at 55 km
- Dense and opaque clouds from 65-45 km
- High altitude balloon missions (at 55km) are feasible and have been successful for 48h limited by the primary battery energies, which only survived for 2h in the surface missions.
- Low altitude missions are more challenging (more so at the surface) due to lack of adequate thermal stability for the power sources, electronics and other spacecraft components
- Divided over four zones based on the energy storage technology options

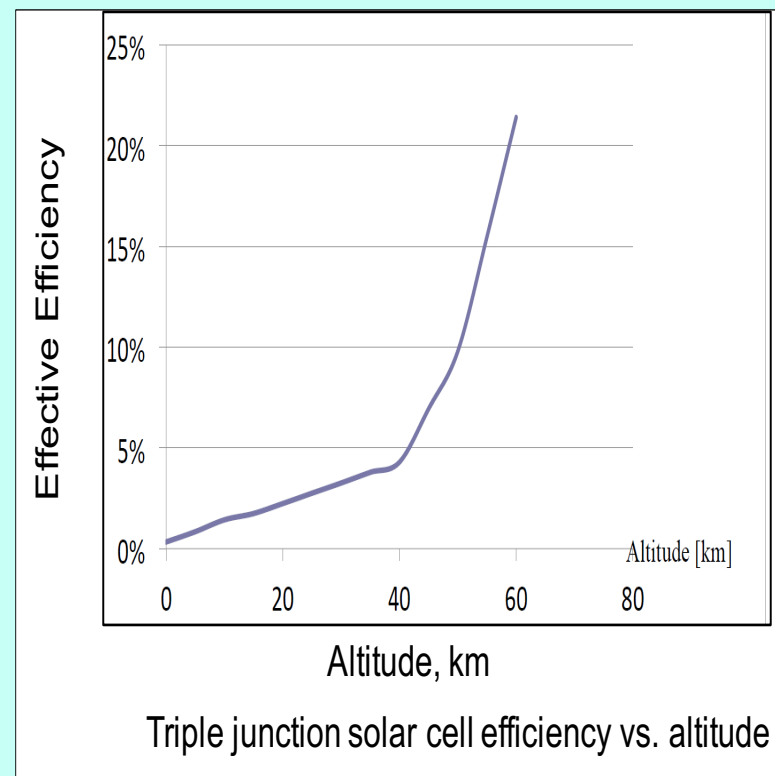


Here we describe different energy storage technologies for different zones (altitudes).

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Need for Energy Storage Systems

- Energy Storage Technology is generally needed to augment the main power sources
 - For load levelling with an RTG (e.g., MSL, Mars 2020)
 - To provide power during nighttime.
- Due to the opacity of the Venus atmosphere, photovoltaic array is less efficient in and below the clouds and needs to be augmented with a high temperature energy storage
- At the surface or altitudes closer to the surface, photovoltaic or nuclear power systems (radioisotope thermoelectric generator) are challenging. High temperature primary batteries would be only viable near-term solution.
- *Crucial need for new long-lasting power technologies to enable extended low-altitude aerial mission concepts.*



Here we describe three different classes of power systems for supporting the surface missions, aerial platforms and long-duration variable altitude balloons utilizing in-situ resources.

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Temperature Ranges of Various Energy Storage Technologies

Battery Technology (Temp)	-40 to 60C	60 to 150	150 to 260	260 to 360	360 to 460	460 to 560	560 to 660	660 to 760	760 to 860
Li-SO ₂ Primary (-40 to 70C)									
Li-SOCl ₂ Primary (-40 to 160C)									
Li-ion Rechargeable (-30 to 70C)									
PEM Fuel Cell (Nafion) (25-100C)									
PEM Fuel Cell (PBI) (50-200C)									
Na-S (250-400C)									
Na-MCl ₂ (250-400C)									
Solid Oxide Fuel Cell (800C)									
HOTTech Primary Battery (465C)									
HOTTech Rechargeable (465C)									

- *Different technologies exist specific to various different missions*

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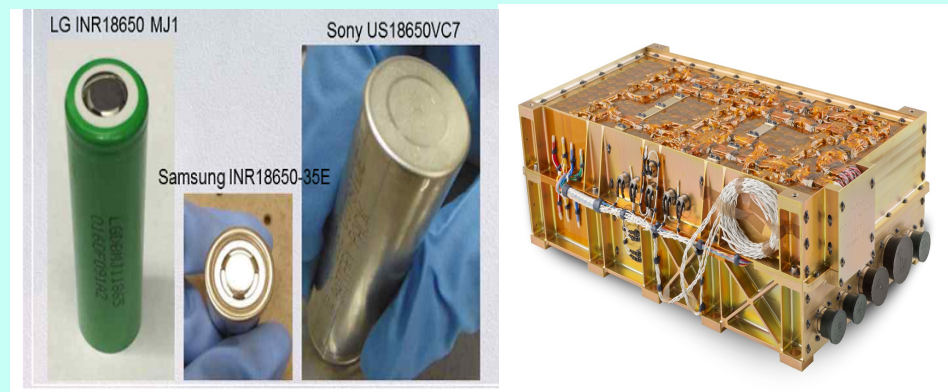
Zone 1 (60-50 km) High Altitude Aerial Platforms

High energy Rechargeable Batteries for -10 to +70°C

• Near-term Option

- High specific energy Li-ion batteries using COTS technologies
- 260- Wh/kg and 700 Wh/l at the cell level and ~200 Wh/kg at the battery level.
- Operational over -10 to 70°C
- Cycle life: 500-100 cycles

TRL 5



• Future Options

- Lithium-sulfur batteries
- >400 Wh/kg at the cell level and 300 Wh/kg at the battery level

TRL 3

C/10 at RT	Panasonic NCR GA	Samsung 3.5E	Sony VC7	LG MJ1
Discharge Capacity (Ah)	3.34	3.49	3.5	3.41
Discharge Energy (Wh)	12.16	12.7	12.72	12.46
DC Internal Resistance (mohm)	38	35	31	33
Average Mass (g)	47	46	47.4	46.9
Average Volume (L)	0.0173	0.0173	0.0173	0.0173
Specific Energy (Wh/kg)	259	276	269	266
Energy Density (Wh/L)	704	733	735	720

Would support long-term exploration (in conjunction with a PV array) at 60-50 km

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Zone 2 (55-40 km) High Altitude Aerial Platforms

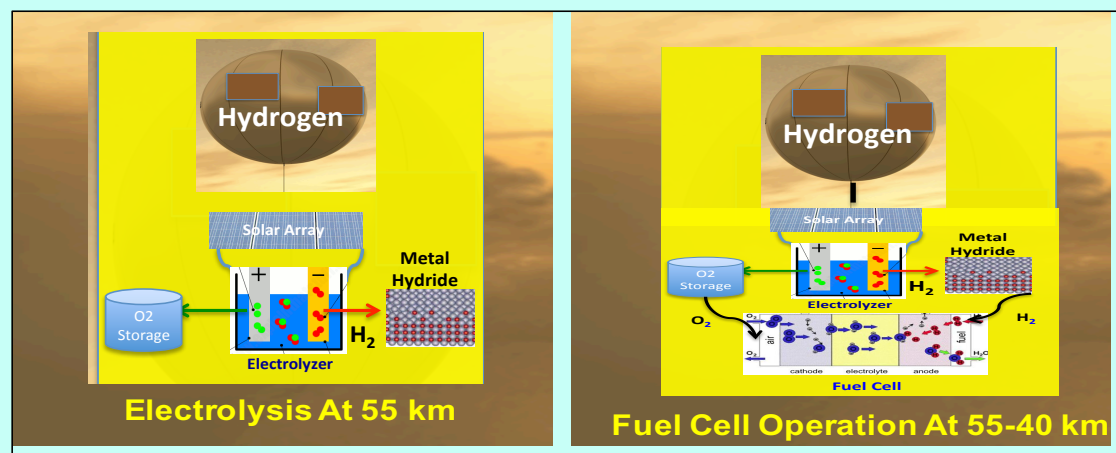
Fuel Cells or Batteries for 25 to +150°C

• Near-term Option

- Solid proton exchange membrane Fuel Cell (PEMFC):
 - Perfluorosulfonic acid (PFSA) polymers, e.g. Nafion®, 25-100°C for 25- 100°C.
 - PBI acid-doped polybenzimidazole (PBI) membrane for 50-200°C.
- A novel architecture for 25-150°C
 - A PBI-based fuel cell for powering the aerial vehicle from 55-40 km,
 - A Nafion-based electrolyzer for regenerating H₂ and O₂ at 55 km,
 - Suitable metal hydrides (MH) for H₂ storage: attractive, as they absorb H₂ readily at high altitudes and release at lower altitudes.
 - Specific Energy: >300 Wh/kg
 - Cycle life: >500 cycles
 - Lifetime: >10000 h

TRL 5

- Due to the opacity of the Venus atmosphere, orbital/balloon observations are inadequate to take visible images of the Venus surface



Dual Fuel Cell Power Source for Variable Altitude (55-40 km)

• Future Options (TRL: 2-3)

- Rechargeable batteries with solid electrolytes or molten salts
- >300 Wh/kg at the cell level and 200 Wh/kg at the battery level

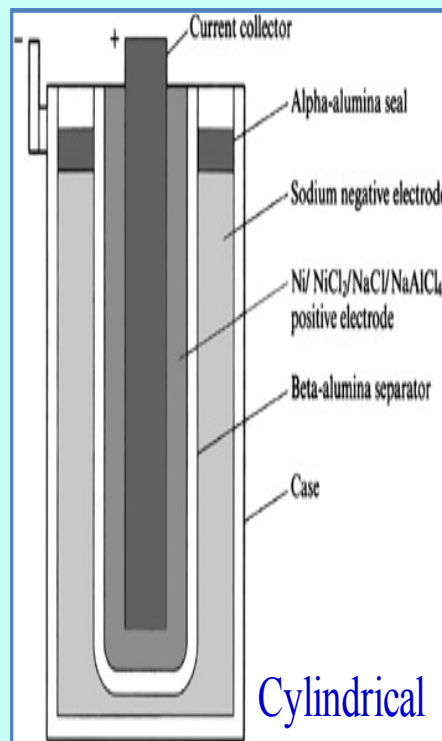
Would support long-term exploration (in conjunction with a PV array) at 55-40 km

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Zone 3 (55-20 km) Variable (and Low) Altitude Aerial Missions

High Temperature Rechargeable Sodium Batteries for 250-350°C

- Same chemistry as the commercially available sodium-metal chloride (termed 'ZEBRA' batteries) with: i) molten Na anode, ii) sodium β -alumina solid electrolyte separator, iii) molten sodium tetrachloroaluminate catholyte and iv) solid nickel chloride cathode.
- New high temperature, long cycle and long calendar life rechargeable battery, operational from 190°C to 350°C.
- Safer (vs Na-S) and the most mature high temperature battery system developed for vehicular applications, and for grid scale and stationary applications.



Sodium-Metal Chloride Cell

Characteristic	Na-NiCl ₂
Operating Temp Range, °C	250 - 500
Open Circuit Voltage, Volts	2.58
Theoretical Specific Energy, Wh/kg	800
Specific Energy for Cells, Wh/kg	100-130
Specific Energy for Batteries, Wh/kg	90-110
Energy Density for Cells, Wh/l	150-190
Energy Density for Batteries, Wh/l	70-130
Cycle Life, cycles	>2000

Batteries kept warm at all altitudes

Would support long-term exploration (in conjunction with a PV array) at 55-20 km

TRL: 5

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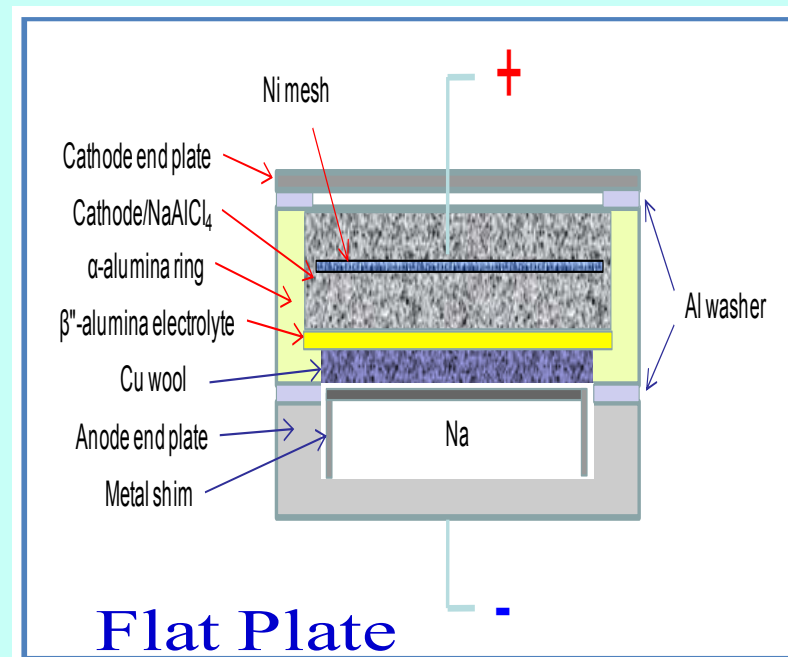
Zone 3 (55-20 km) Variable (and Low) Altitude Aerial Missions

High Temperature Rechargeable Sodium Batteries for 190-350°C

- New planar geometries for improved specific energy and operational capability at lower temperatures
- Performance: Batteries operate from 190 through 350°C, i.e.,
- High specific energy (>300 Wh/kg) projected from laboratory cells
- Excellent life (>1000 cycles and 5 years) based on the solid electrolyte system
- Benefits: Will be leveraged from terrestrial applications (grid batteries) –Rapid maturation
- Currently under development at GE (Durathon), Pacific Northwest National Lab (PNNL), Eagle Picher Technologies

Would support long-term exploration (in conjunction with a PV array) at 55-20 km

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Advanced Sodium-Metal Chloride Cell

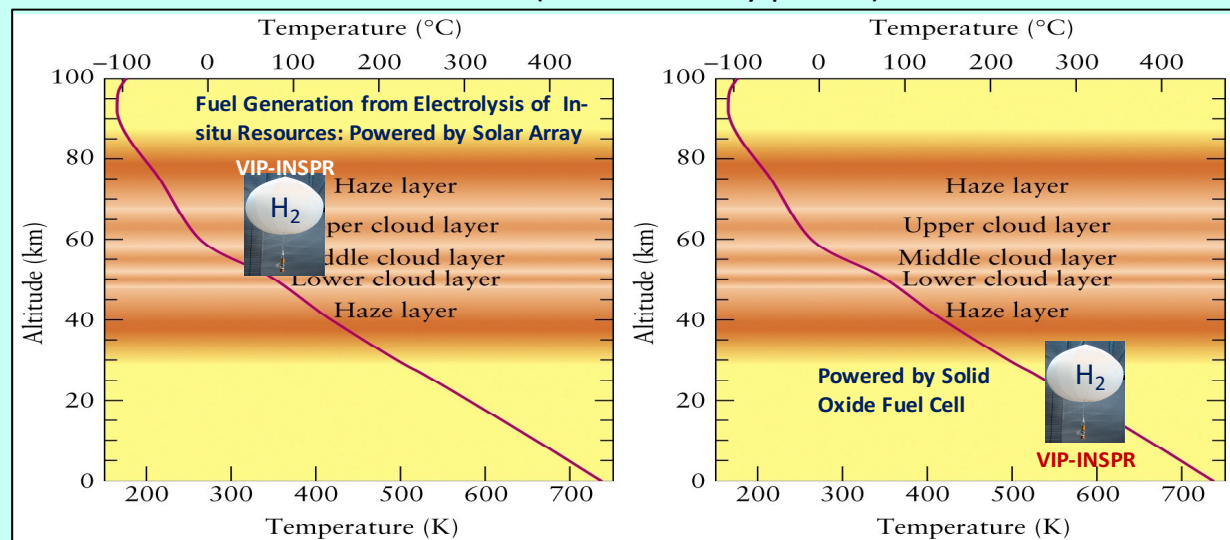
Batteries kept warm at all altitudes

TRL: 4

Zone 3 (55-20 km) Variable (and Low) Altitude Aerial Missions

A Novel Solid Oxide Fuel Cell Based Power Source with In-situ Resource Utilization-NIAC Project

- The Venus Interior Probe Using In-situ Power and Propulsion (VIP-INSPR) is a novel proposed architecture for Venus Interior Probe based on in-situ resources for power generation (VIP-INSPR) and navigation.
- This involves the generation of hydrogen and oxygen at high altitude from *in situ* resources, i.e., solar energy and sulfuric acid/water from the Venus clouds or from the water (steam) produced at low altitudes and generation of power at low altitudes utilizing these resources in a high temperature fuel cell.
- In addition, the hydrogen generated at high altitudes would also be used as a lifting gas to navigate the probe across the Venus clouds for extended durations (not limited by power).



Would support long-term exploration (in conjunction with a PV array) at 55-20 km

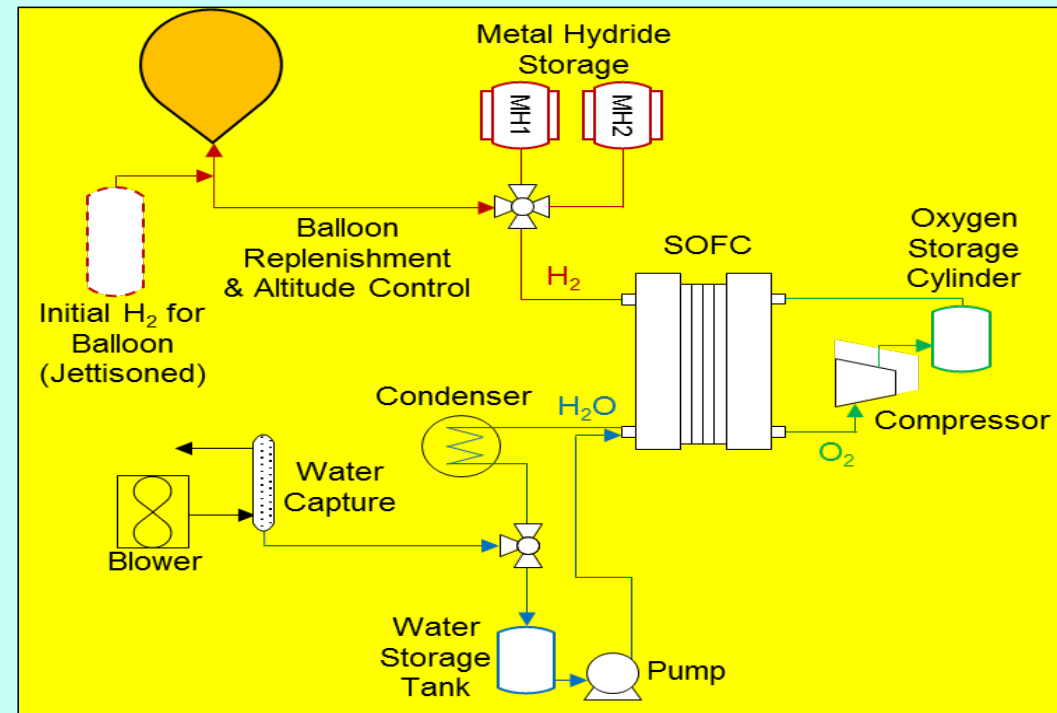
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TRL: 3-4

Zone 3 (55-20 km) Variable (and Low) Altitude Aerial Missions

VIP-INSPIR- Venus Interior Probe using In-Situ Power -NIAC Project

- A Reversible Solid Oxide Fuel Cell (RSOFC) for electrolysis at high altitudes and power generation at low altitudes.
- High temperature tolerant solar array to provide power to the balloon and to the RSOFC to generate H_2 and O_2 at high altitudes
- Harvesting in-situ resources (H_2SO_4 or H_2O) in the upper atmosphere for electrolysis (generation of H_2 and O_2)
- Hydrogen storage in a multi-system wide-temperature metal hydride (MH) (absorption at low T and desorption at high T)
- Electrochemical compression and storage of oxygen
- Balloon altitude control system using MH to store H_2 for descent to low altitudes for subsequent power generation.



TRL 3-4

SOFC maintained at 800°C

Would support long-term exploration (in conjunction with a PV array) at 55-20 km

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Zone 4 Surface Missions

High temperature and Long-life (HiTALL) Primary Batteries (465°C)

- A battery thermally stable on the Venus surface for extended durations and providing high specific energy.
- Configuration:
 - Similar to the current thermal batteries, but with longer life (days vs. minutes).
- Chemistry Improvements
 - High capacity anode (Li alloy),
 - High energy cathode (metal chalcogenides) with improved stability (no stability / decomposition)
 - New molten salt electrolyte with low pressure (mixed alkali metal halides)
 - Separators with low self-discharge.
- Specific energy: >150 Wh/kg, energy density: >200Wh/l, long calendar life (>5y) and low self-discharge (<1%/day) at 500°C.
- Benefits: Lightweight and compact (3-4X vs. SOA) and will support Venus/Mercury surface missions over long durations (>30 days vs < 2h for SOA).
- Being developed under NASA-HOTTech program

Would support long-term (60 days) exploration on the surface of Venus

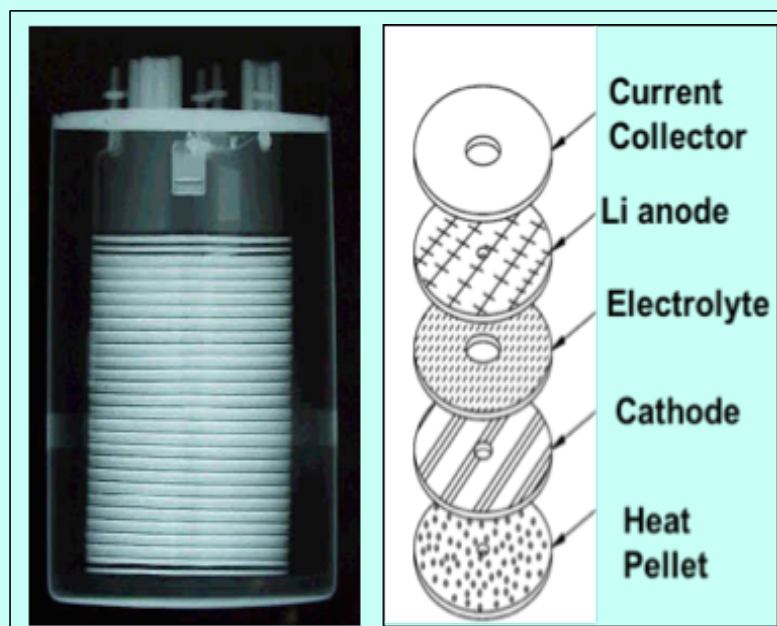
TRL: 4

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Zone 4 Surface Missions

High temperature and Long-life (HiTALL) Primary Batteries (465°C)

Schematic of a High Temperature Battery



Performance Estimates

	MSL Power Thermal Battery	Gen 1 Venus Battery (Design Mod)	Gen 2 Venus Battery (Design Mod + Adv Chemistry)
OD (in)	4.5	4.5	4.5
Length (in)	10	4.3	4.3
Capacity (Ahr)	7.2	7.2	12
Nom. Voltage (V)	33	33	33
Weight (Kg)	5.6	2.7	2.7
Vol. (l)	2.6	1.1	1.1
Specific Energy (Wh/kg)	42	87	150
Energy Density (Wh/L)	91	212	260
Gain in Wh/kg	-	2X	~4X
Gain in Wh/l	-	2X	3X

Would support long-term (60 days) exploration on the surface of Venus

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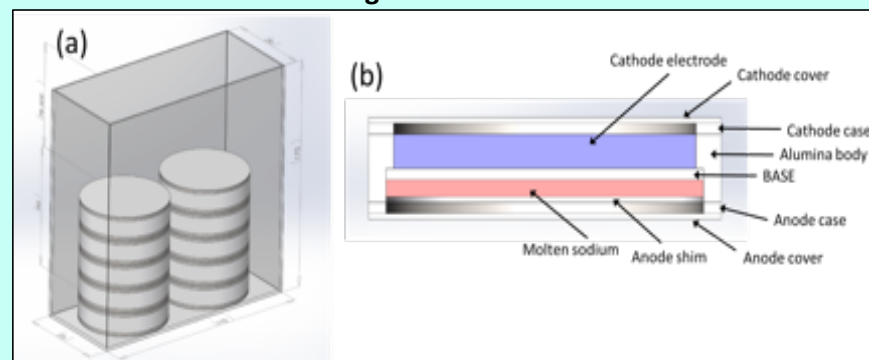
TRL: 4

Zone 4 Surface Missions

High-Temperature Tolerant Advanced Planar Na-NiCl₂ (HiTTAP-NaNi (465°C) Concept proposed (together with PNNL) in support of LISSE

- Similar to the Zebra batteries
- Will develop advanced cell components and materials commensurate with 460°C operation and sufficient energy capacity
 - Advanced planar-type cell architecture,
 - **Reliable glass/Thermo-compression bonding TCB seal,**
 - BASE with sufficient mechanical strength
 - Formula of cathode with higher energy and improved thermal stability
 - Secondary electrolyte (molten salt) **with low vapor pressure**
 - High-capacity and thermally stable Li alloys
- Proposal submitted in support of LISSE but not supported (due to the budgetary reasons)

Schematic view of two stacks (5 cells for each stack) (b) cross section view of each single cell of HiTTAP-NaNi batteries.



Comparison of HiTTAP-NaNi with other High Temperature Batteries

	Na-S	Zebra	IT Na-MH	HiTTAP-NaNi
Anode	Molten Na	Molten Na	Molten Na	Molten Na
Cathode	S	NiCl ₂	NiCl ₂	NiCl ₂
Solid-state Electrolyte (SSE)	β"alumina	β"alumina	β"alumina	β"alumina
Shape of SSE	Tube	Tube	Disc	Disc
Temperature (°C)	350	280	190	460
Specific Energy (Wh/kg)	~150	~100	~150	~150
Compactness (7x17x17 cm)	No	No	Yes	Yes
Sealing Technology	Glass/TCB	Glass/TCB	Polymer	Glass/TCB
Lifetime	>10 y at 250-300C			> 6 months at 460C
Feasibility for LLISSE	No	No	No	Yes

Would support long-term (>6 months) exploration on the surface of Venus

TRL: 3

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